

## THE TIDES : WITH SPECIAL REFERENCE TO THOSE OF FREMANTLE AND PORT HEDLAND.

By

H. B. CURLEWIS, B.A., F.R.A.S., Acting Government Astronomer.

### INTRODUCTION AND SCOPE OF THE PAPER.

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A short summary of what was known about the tides in early times and a brief reference to the main theories that have been advanced to account for their behaviour will be given at the outset of this paper in order that there may be a proper understanding of some of the points which are discussed in connection therewith.

As far back as the first century B.C., it was realised that there was a dependence between the moon and the tides, but the reason for this connection was not known until the seventeenth century, when Sir Isaac Newton explained it as due to the force of gravitation exercised by the moon upon the waters of the ocean, and later on postulated that the sun must exert a similar influence.

Naturally Newton was not satisfied with the bare statement of this fact but elaborated a mathematical theory which is known as the "Equilibrium Theory." It demands, in brief, that the tidal cone of water should be under the moon—reference to the sun is omitted because mention of it only complicates matters and makes a simple explanation impossible—but the sun's attraction has to be considered equally with the moon's. It was called the Equilibrium Theory because the moon is supposed to act for an appreciable time upon any single part of the ocean and therefore that portion might be treated as if it were at rest or in a state of equilibrium. It is rather peculiar that the most trustworthy records then available, namely those of Cadiz, clearly place the high water under the moon. However, when Newton came to investigate the tides of the English coasts, he found so many discordances to this necessary postulate that he became dissatisfied with and mistrustful of his original theory, though he never lived to make any material alteration to it. About a hundred years later, however, Laplace formulated his famous Dynamical Theory which, as far as the then known tides were concerned, brought about satisfactory harmony between theory and actual fact. And yet, had tidal records from America, India, and the southern hemisphere been available, it is highly probable that the dynamical theory would never have been evolved, for the great majority of these tides do not conform to it. Whereas the equilibrium theory does offer a reasonable explanation of what actually takes place or at any rate enormously reduces the number of anomalies.

It is difficult to explain in a few words what is meant by the dynamical theory, but speaking generally the position of the tidal cone according to this theory depends mainly upon the rotation of the earth upon its axis, and the cone of water would be in great part due to a heaping up of the water owing to centrifugal force and would of necessity travel along lines parallel to the equator. In contradistinction to this the equilibrium theory, as already mentioned, demands that the cone of water is drawn up by the gravitational attraction of the moon and sun.

This main distinction between the two theories must be carefully borne in mind, especially in the case of the Port Hedland tides, so that the arguments in favour of the equilibrium theory may be appreciated when these tides are examined in detail.

A glance at Plate VIII., Fig. 1, entitled "Diagram explaining Diurnal Irregularity," will make one of the arguments in favour of this theory quite clear. The central circle represents the earth and the shaded area an imaginary shell of water—enormously exaggerated in proportion to the size of the earth. The moon is supposed to be at M, at its furthest distance from the equator and the maximum bulge of water is occurring under and opposite to M. Now it can be readily seen that a port at H where a high tide is taking place, will be carried by the earth's rotation on its axis, SN, through a low water at L to another high water at H<sup>1</sup> and here, owing to its being nearer to the major axis of the ellipsoidal shell of water, the tide is higher than at H. As the moon approaches the equator, it carries the tide-bulge with it and the difference in height between the H and H<sup>1</sup> becomes less and less, until at the equator it vanishes. It should be further noticed that as the moon travels to the other side of the equator, the H tide becomes higher than the H<sup>1</sup> tide. When the tides of Port Hedland are examined it will be found that their behaviour can be explained by reference to this diagram, and to a lesser extent the action of the Fremantle tides. So much by way of introduction.

Before, however, discussing in detail the Fremantle and Port Hedland tides, a brief reference to the history of tidal observations in Western Australia will not be out of place.

#### TIDAL OBSERVATIONS IN WESTERN AUSTRALIA.

Probably on no coast in the world is there less exact knowledge of the tides than on the coast-line extending from Wyndham in the far north to Eyre in the extreme south-east, and therefore it will not be surprising to learn that satisfactory records have been taken at only one port, namely Fremantle.

As far back as 1873 the Admiralty recognised the importance of a knowledge of the tides on the Western Australian coast and caused a series of observations to be carried out at Fremantle. The work was performed chiefly by Staff-Commander Archdeacon, R.N., the officer in charge of the Admiralty Survey of the coast and per-

force only extended over a comparatively short period, but long enough to prove that the Fremantle tides were extremely interesting from a scientific point of view and called for a series of observations extending over many complete years before a correct interpretation of their numerous anomalies could be given. In spite of this, however, on the discontinuance of the Admiralty work nothing further in the way of tide-recording was attempted for many years.

In 1900, following on recommendations by Captain Irvine, the Chief Harbour Master, and by Mr. Cooke, the Government Astronomer, a number of Bailey's tide recorders were purchased and in the course of time gauges were established at Fremantle, Bunbury, and Albany, and later on at Port Hedland. For a long time the records from these gauges were stored away and put to no use—the result showed what a mistake this was.

In 1911, however, a very progressive step was taken—the appointment of a computer to undertake the compilation of these records. The work was commenced at the Observatory under my supervision, owing to absence of Mr. Cooke who was at the time in England. A start was made on the Fremantle figures, which, as it turned out, were the only ones that had been properly kept. When the records from the other ports came to be examined at the Observatory, it was found for various reasons that it was impossible to obtain satisfactory readings from them.

This was much to be deplored and only proves how essential it is that constant and expert supervision should be kept over work of this nature. The figures obtained from the Fremantle records for the years 1908 to 1912 were compiled and finally treated according to the method of harmonic analysis proposed by Sir George Darwin and the one now universally adopted. A brief explanation of this method and the results of the analyses appear at the end of this paper.

#### THE PORT HEDLAND TIDE GAUGE AND RECORDS.

As already mentioned, the records taken at the above port were found to be valueless, not only on account of the number of breaks in the records, but because the scale of the Bailey tide gauge was far too small and proved quite inadequate for the registration of such a wide range of tide as is experienced at Port Hedland. It was therefore decided to have a gauge of more suitable design constructed, and Messrs. Jones & Co., of Perth, under the supervision of Mr. Yeates, of the Observatory, were entrusted with the work. The new gauge—a photograph of which is reproduced (*vide* Plate IX., Fig. 1)—departs somewhat from the usual form of tide-recording instrument, in that it is the pencil, and not the drum, which is operated by clock-work. The drum itself is directly attached to the tide-float and turns backwards and forwards as the float rises and falls with the tide. In order to eliminate wave action the float is free to pass up and down an enclosed cylinder which at Port Hedland consists

of a heavy iron tube over 20 feet in length, weighing at least a ton. In the photograph may be seen the cord, with weight (invisible) attached, passing over the small pulley-wheel on the left, and connecting on to the pencil carrier which moves along two parallel slides. Attached to the other side of the carrier is the other cord, passing round the small wheel on the right, and thence up to the clock—an ordinary “Ansona.” At the back of the clock it winds round a cylinder fixed to an extension of the centre-arbor. As the clock gradually runs down, the weight draws the pencil carriage along the slide a distance of approximately twelve inches in the twenty-four hours. A long chain, made from bicycle chains, passes over two gear-wheels, and attaches to the float on the right-hand side (neither float nor any portion of the well appears in the photograph). The top gear-wheel engages in a small cog-wheel on the end of the axis of the drum, and gives the rotary movement to it. It is so geared up that a foot rise or fall corresponds closely to half-an-inch turn of the drum. The chain passes down over a lazy-pulley and is made fast to a counterpoise weight. The cylinder or drum is fifteen inches long and six inches in diameter. It is placed horizontally on a solid stand beyond which one end of its axle projects, engaging by the system of gear-wheels mentioned above upon the eight-inch B.S.A. wheel.

In the majority of tide-gauges the pencil is operated by the float and the drum, with its axis placed either horizontally or vertically, is driven round by clock-work. By introducing the above radical change in the Port Hedland gauge a more easily decipherable tide curve was ensured and a distinct improvement in the adjustment of time was expected. For it can be readily understood that it is not necessary to depend upon the clock which draws the pencil-carriage along, for the time. This is marked on the sheet at the beginning and end of a day's run, and may be obtained from the local post-office. The sole purpose of the clock is to give uniform motion to the pencil, and so long as its rate does not materially vary during each twenty-four hours it is possible to fix with great accuracy the exact instant of any point on the tide curve. Thus, if the sheet were put on at nine o'clock and taken off at the same time next morning, then it is only necessary to divide the horizontal line between these two marks into twenty-four equal parts and we have every hour of the day marked on the sheet. Two examples of the tide curves registered at Port Hedland on this instrument are reproduced (*vide* Plate IX., Fig. 2, and Plate X.) to show what a clear, widely-spaced trace is obtained. It must be borne in mind that they are on a scale considerably reduced from the original sheets, which measure thirteen inches in length; the height being correspondingly increased. Incidentally, the photographs are examples of “spring” and “neap” tides respectively and clearly indicate the marked difference between the two types. It will be noticed that the high waters appear at the bottom of the sheets, which is rather confusing, perhaps, but owing to the nature of the gauge it cannot be avoided.

The records for the year 1913 have been tabulated and analysed; the tidal constants thus evolved appear at the end of this paper.

Before leaving the Port Hedland tides it will be interesting and instructive to examine in detail the tidal trace for the month of June, 1913, of which a copy is reproduced (*vide* Plate XI.). It should be explained that this is not an absolute copy but is plotted from the actual times and heights obtained from the original sheets. This procedure was adopted in order that the confusion resulting from the high water appearing at the bottom might be obviated, for in plotting it was quite a simple matter to arrange this without in any way altering the curve.

It will be noticed that the curve is divided into four parts, each part representing the record for one week. Thus the first line commences at 6 a.m. on the first (Sunday) and finishes at 6 a.m. on the following Sunday, while the second line commences where the first line terminated, namely at 6 a.m. on Sunday (8th) and so on with lines three and four. The curves for the corresponding days of the week are thus found in the same vertical line. The height scale is shown at either end and runs from 5ft. to 25ft. Only the even hours of the day and night are marked along the top—"Day 12" being noon, while "Night 12" stands for midnight and the commencement of the day. Along the 25ft. line the approximate times of transit of the moon for the meridian of Port Hedland are noted with short black lines, the lower transits being distinguished from the upper by small extensions at the bottom of the line. Along this line the phases of the moon are also shown, the black spot standing for "New Moon," the spot darkened on the right-hand side being the "First Quarter," the white spot "Full Moon," and the spot darkened on the left-hand side representing "Last Quarter." Along the 5ft. line the day on which the moon was furthest north, on the equator, and furthest south is marked, as also the times of "Perigee" and "Apogee," namely when the moon was nearest and farthest away from the earth.

The first striking peculiarity noticeable in connection with these tidal curves is the difference between the two high tides or the two low tides of each day. In nearly every instance the night tide is from six inches to almost two feet lower than the day tide. Reference to the diagram "Diurnal Irregularity," Plate VIII., Fig. 1, will explain how this comes about.

Continuing the investigation and bearing in mind the changes in position of the ellipsoidal shell of water resulting from alterations in the moon's position, it will be found, as would be expected, that when the moon is at its greatest distance north or south of the equator the maximum difference between alternate high waters occurs, amounting to 1ft. 10in. and 1ft. 6in. on June 6th and 19th respectively and more than that, the highest of the two falls on the 6th when the moon was between one and two days old and consequently the two bodies, the sun and moon, would be close together when

passing the upper meridian. This point lends additional weight to the equilibrium theory under which, as I have stated before, the cone of water attempts to place itself under the sun and moon and according to which that tide would be greatest which is directly under and not opposite to the two bodies—notice how the tides of the 6th conform to this argument. And if these tides are compared with those of the 19th additional weight is given to the theory from the fact that on the 6th when the sun and moon are both north of the equator, the tide is higher than on the later date when the sun is north but the moon south.

Another feature of the tides, familiar to everyone, namely its daily retardation, is also clearly brought out. Just as the moon, owing to its movement eastwards along its orbit, rises later every day, so the tidal cone, since its progress is governed in great part by the moon, suffers retardation. The mean retardation of the moon for these 28 days in June amounts to 50 minutes and for the same period the tidal retardation works out at 49 minutes. This agreement is very striking and proves how closely the progress of the tidal wave depends upon the moon. Turning to the tide curves for June once more and noting the times at which the alternate high tides occur, it will be observed that on June 1st the high tide took place at 8.15 a.m.; on June 2nd at 8.44 a.m.; on June 3rd at 9.48 a.m.; on June 4th at 10.16 a.m., and so on—the crest of the morning wave gradually becoming later every day, until by June 15th the retardation amounts to over 12 hours, and naturally the high tide which occurred in the morning on June 1st has now become on the 15th the evening tide. It will also be noted that the times of high and low waters on the 15th are very nearly the same as on the 1st. If the curve could be followed to the end of the month, it would be found that this evening tide became in turn the morning tide of the 29th.

From all this it will be seen at once that so far as the times of high and low water are concerned the tides repeat themselves very closely every fortnight, or, more exactly, every half of a lunation.

Other interesting features come to light on inspecting the curve. Thus, during the first fortnight, the range of tide was greatest on the 6th and 7th—the largest variation in level between consecutive high and low waters being 18 feet, namely between the mid-day high tide and the afternoon low tide; while the smallest variation occurred between the evening high tide of the 14th and the morning low tide of the 15th, when the difference amounted to  $7\frac{1}{2}$  feet. From this time on the range increases until the 19th and 20th, when it was approximately 17 feet and then it begins again to diminish, reaching a minimum of  $5\frac{1}{2}$  feet on the 28th.

A glance at the moon's phases shows that it was "New" on the 5th and "Full" on the 19th, while "First and Last Quarters" fell on the 12th and 26th respectively. The tides which occur about the time of new or full moon are termed "spring" tides, while those

which happen near the time of first or last quarter are called "neap" tides. The information that has just been obtained from the curve clearly discloses the relationship existing between the spring and neap tides and the phases of the moon.

Still another point must be noted: the tides of the 10th, roughly a day before "First Quarter," are higher than those on the 25th, a day before "Last Quarter"; whereas, conditions being the same, tides of the same height would have been expected. The reason for the discrepancy is not hard to find: on the 10th the moon was in perigee or at its nearest distance to the earth, while on the 25th it was in apogee or further from the earth than at any other time during the month, and hence the moon's attraction on the 25th would be less than on the 10th and consequently the tides would be lower.

Summarising what has been so far discovered from an examination of these June curves, the connection between the moon and the tides has been demonstrated beyond doubt. It has been clearly shown that the height or range of the tides depends chiefly upon the phase of the moon and in a minor degree upon the distance of the moon from the earth. The highest tides of all would therefore be expected when these two causes act together, namely when new or full moon occurs at a time when the moon is also nearest to the earth or in perigee. To verify this, it will be necessary to run through the whole year's records and pick out the readings on the days when the above coincidences take place. The following dates, picked out at random, must suffice:—On September 1st the moon was "New" and nearest to the earth, the high water was 26ft. 9in. and the low water 3ft. 11in.; while on the 15th, when the moon was "Full," the tide only rose to 25ft. and fell to 5ft. 1in., but on this date the moon was in apogee. Again, on February 7, new moon occurred at apogee and the tides were 24ft. 4in. and 6ft. 3in. high and low water respectively. With which contrast the 21st, the moon being "Full" and in perigee, when there is a high tide of 27ft. and a low of 4ft. 7in. according to the tide trace. It should be remarked that owing to the tide gauge being about 9ft. above the datum line, this quantity must be taken from the readings given to obtain the exact height of the water level.

The relationship between the tides and the phases of the moon would at once prove that the sun, even if the fact were not already known, plays a very important part in tidal phenomena, and an examination of the constants for Port Hedland at the end of this paper shows that the mean solar is responsible for a tide about one-third that of the mean lunar. And this is exactly what we would expect from theoretical reasoning. It can be understood in a general way when it is realised that the tide-generating force varies directly as the mass and inversely as the cube of the distance of the tide-generating body. Thus, although the sun is enormously larger than the moon, its tide-lifting force is only one-third that of the moon. It is quite easy to demonstrate this from the known distances and

masses of the two bodies. Full information on this point and many others dealing with the tides can be obtained from almost any text-book on the tides, and perhaps for preference *The Tides*, by G. H. Darwin. Without, however, going into these points it will be seen from the curves that at new and full moon when the sun and moon are in line, the maximum tides occur and are known as "Springs"; while at first and last quarter the tidal range is only about one-third that of the springs, and these are called "Neaps." Under ideal conditions this would probably apply but in practice, as in the Port Hedland tides, the spring and neap tides occur one or two days after the changes of the moon. Reference has already been made to good examples of spring and neap tides in October (*vide* Plate IX., Fig. 2, and Plate X.). At the time of the Equinoxes the highest springs and the lowest neaps of the year will generally be found. The ready explanation being that the sun is then on the equator and consequently the new and full moon must be on the equator also, and thus towards the end of March and September the highest tides may be looked for simply because the two great tide-generating bodies are exerting their respective pulls along exactly the same line.

So far these tidal curves have borne out what would be expected to take place according to the Equilibrium Theory except that the height of the tide is considerably greater than what would be looked for under ideal conditions. There are, however, a number of factors which singly or collectively would account for this apparent anomaly. The chief of which would be, firstly, the depth of water; secondly, the speed of the wave—this is simply a corollary of the first; thirdly, the configuration of the coastline, and fourthly, the direction of ocean currents caused by the earth's rotation and by the distribution set up by the difference in temperature between equatorial and polar waters. (There are probably other causes, but these must suffice.)

Now it is a fact well known to everyone that an ordinary ocean roller gradually becomes steeper as it approaches a shore which shelves upward—Cottesloe Beach for instance. And so with the tide-wave: in the open ocean it has a maximum of about three feet, but when the ocean bed shelves upwards, then the height of the tide-wave is increased. The shallow, shelving ocean floor along the North-West coast is undoubtedly the main cause of the high tides there. At many places the height is still further augmented by the shape of the coast-line, as for instance at Derby, situated at the head of King Sound, where tides of 36ft. occur. However, there is not sufficient data available to adequately discuss the reasons for the high tides along the North-West and Kimberley coasts.

Returning once again to the tide-curve for June, at first glance the crest of the wave or high water comes fairly well under the moon, namely, coincides with the moon's transit at new and full, as the equilibrium theory demands, and gradually lags behind as first and last quarter is approached. A closer inspection shows that the high water is twelve to nine hours after the moon's transit. If

figures from other ports on the coast were available, it would probably be found that this interval between the moon's meridian passage and the time of high water varied widely—so widely that it would seem impossible to reconcile the equilibrium theory with the discordant results. However, the four factors just mentioned would be quite sufficient to account for all the different intervals that may exist, and hence it is not fair to say that the theory breaks down because the crest of the wave does not occur approximately under the sun and moon at all places about the time of new and full moon. In connection with wave transmission it is worth remembering that a wave travels faster in deep water than in shallow, and hence the lag of the tide-wave behind the moon must vary directly with the different depths of the ocean along the coast. At some future time, when the importance of tidal work has been recognised in Western Australia and observations taken at all the ports, a complete discussion it is hoped will be undertaken.

The time that elapses between the moon's meridian passage and high water is termed the Luni-tidal Interval, and if these intervals are plotted, using the moon's meridian passage as an argument, a curve results which is known technically as "The True Establishment of the Port." Plate XII., Fig. 1 shows the Establishment for Port Hedland. To make use of the diagram the time of the moon's transit, taken from the Nautical Almanac, is noted on the top or bottom line, and then the point on the curve vertically above or below. From this point the horizontal line is followed to the time scale on either side, giving the luni-tidal interval, which, added to the time of moon's transit, gives approximately the time of high water. To obtain a more accurate result corrections for the sun's position, the moon's declination, and the time of the year must be added.

It stands to reason that this rough and ready method is only applicable at places where the tides are fairly regular; it would break down in cases where the tides are irregular or do not depend in the main upon the moon. Thus at Fremantle, as will be found later on in this paper, it would be impossible to determine any definite curve.

Just as a rough rule for finding the time of high water can be made out, so in the same way curves can be drawn, having the moon's meridian passage as argument, from which the approximate heights may be estimated. Thus Plate XII., Fig. 2 provides a means of finding the height of high and low water and consequently the range of the tide at Port Hedland.

#### THE FREMANTLE TIDES.

Turning now to the Fremantle tides it will be found that the matter becomes very much more complicated and not nearly so easy of elucidation. As mentioned above it is impossible to make a curve of the luni-tidal intervals; nor is it possible to show on a diagram the height or range of the tide depending upon some determinable

argument. It will be found from observations that there is no such thing as spring or neap tides as would be naturally expected. In fact, there are few places in the world where tidal complications are so pronounced as at Fremantle. I cannot do better than repeat some of the remarks that I made when publishing the Fremantle tide tables for 1913.

They (the Fremantle tides) are not marked by the comparative simplicity that obtains in the tides of British and European waters, where in many cases the interval elapsing between successive meridian passages of the moon and the time of high or low water is almost invariably a constant quantity or closely approximates to such and where the heights of consecutive high waters and of consecutive low waters follow a fairly constant law, but on the contrary the differences in heights and the inequalities of successive intervals appear to the casual glance to be governed by no fixed law, but seem to be as variable and capricious as the weather. This peculiarity can very probably be accounted for by the disturbing influences of the wind and weather on the comparatively small range of tide prevailing at Fremantle which, except at certain short periods during each month, when it exceeds two feet six inches, rarely averages more than eighteen inches, thus should a strong easterly or nor'-easterly wind be blowing the theoretical time of high water is almost certain to be delayed and the height also diminished. On the other hand, the sou'-wester or sea breeze banks up the water to a greater or less degree, dependent upon its intensity, accelerating the time of high water, augmenting its height and prolonging its duration. This would be especially noticeable during a westerly blow, and the exceptional height often reached by the tides during the winter months is almost solely due to the banking up of the water against our western coast line; although in this connection, it must be remembered that the great tide wave which travels along the South coast of the continent from east to west is retarded by a westerly wind, and its height necessarily increased, and consequently there occurs an additional banking up of the water of the ocean off Cape Leeuwin, which makes its effect felt to a greater or less extent northwards.

These reasons explain why a continued and perhaps exceptionally high tide often heralds the approach of a cool change in summer or of a Nor'-West storm in winter. In this respect it must be borne in mind that the ocean is affected by atmospheric pressure to a slight extent, the surface of the sea rising with a low and falling with a high barometer. Theoretically there is an alteration of level corresponding to one inch for every one-twentieth inch of mercury.

But it must not be imagined that the absence or elimination in some way of these disturbing elements would cause the Fremantle tides to be marked by the same regular law or laws that appear to prevail in the case of those in European waters. On the contrary, it is almost safe to say that their peculiar irregularities would be

just as much in evidence. The use of the words "peculiar irregularities" in connection with them is, perhaps, inaccurate, and is only justified by comparison with the tides of the North Atlantic, which are really exceptional in their simplicity. There are probably many other ports in the world where the tides are just as uncertain.

Although the luni-tidal interval, namely, the time that elapses between the moon's meridian passage and the following high tide, is subject to every possible variation, to such an extent that no reliance can be placed upon this method of predicting the time of high or low water, still an examination of the Fremantle tides bring some interesting features to light.

Thus when the moon is in Perigee the tides are invariably higher and the range greater than in Apogee. This is only to be expected, for its attractive force is then at a maximum. So in this respect, at all events, the Fremantle tides conform to the generally recognised law. On the other hand, we might expect to find some regular sequence of change existing between the tides and the phases of the moon, but a comparison between the times and heights of high and low water with the age of the moon fails to disclose any existing connection, in fact, if only still further serves to emphasise the complications present in the tide-governing forces, and to demonstrate the difficulties likely to be met with in an attempt to accurately explain them. For the greatest and least ranges occur both at the change and full of the moon alike.

It should be noted in this comparison that at about the time of first quarter and again at last quarter the diurnal tide, namely one high and one low during the day, is almost invariably in evidence. It also may be taken as a general rule that the highest tides and greatest range occur about the time of moon's first quarter, although this sometimes breaks down. At the time of full or new moon the semi-diurnal tides often make their appearance, marked by small range and great irregularity. But it sometimes happens, as mentioned above, that the highest tides and the greatest range take place at these times, with the almost certain prevalence of a diurnal tide.

A comparison, however, with the moon's position in declination shows that when the moon is on the Equator, the least range occurs, the variation in water-level being about one foot, and also great irregularity in the times of high and low water is apparent. Very little reliance can be placed upon the tidal predictions at this period. Often for quite a considerable length of time the water remains unchanged in level. The semi-diurnal tides, namely, two highs and two lows during the twenty-four hours are also in evidence, but the secondaries are sometimes barely perceptible, the difference between the heights of this inferior high and low water being only a few inches.

As the moon moves North or South of the Equator, the range gradually increases and the tidal curve becomes regularly diurnal

in character. More dependence also may be placed upon the predicted times as the moon's distance from the Equator increases.

Contrary to what might be expected the highest tide and greatest range happen when the moon is at its farthest North point, and not at its greatest South declination, when the moon would be almost directly over Fremantle, and would thus be in a position to exercise the maximum attractive force on the water.

It may be stated, therefore, with some degree of certainty, that the Fremantle tides depend to a large extent upon the moon's declination, and from its position the range of tide may be gauged fairly accurately, but the irregularity in the occurrence of successive highs and lows, although most marked when the moon is on the Equator, is still to be expected when the moon attains her greatest North or South declination.

On Plates XIII. and XIV. copies of the Fremantle tides for June and October, 1910, have been plotted in the same way as the Port Hedland curve for June, 1913, shown on Plate XI., so it is not necessary to repeat the explanation of the different lines and figures.

The first thing that strikes the observer is the unevenness of the trace compared with that of Port Hedland. The same gradual rise and fall of the water level is absent and in addition there is generally only one high and one low during the twenty-four hours. This affords perhaps the most striking difference between these two tides, for whereas the tides of the northern port are almost without exception semi-diurnal, namely two highs and two lows every twenty-four hours, those of Fremantle are, as just noted, diurnal. The semi-diurnal sometimes puts in an appearance but it is only a very half-hearted attempt. A close inspection shows that some of the arguments in favour of the equilibrium theory hold even with these tides, but they are not nearly so self-evident.

It will be noticed that in June, when the tides are diurnal, the high water seems to follow the sun by an hour or so, and consequently the low tide occurs at night, but this is not invariably the case, for a glance at the October trace shows that, when distinct diurnal tides take place, the high water occurs at night.

In order that the effect of the weather upon the tides may be appreciated, along the bottom line for each day the barometer reading and the wind with its velocity are inserted. The north-west and west winds, which along the west coast generally spell stormy conditions, will be found to cause an appreciable uplift of the water level; for an example of this notice the abnormal heights of both high and low tides from the 5th to the 8th and again on the 26th and 27th. The same result is apparent in October, especially on the 16th. And many of the other points in the main remarks on the Fremantle tides may be verified by reference to these charts, but nothing of the same convincing nature is brought to light as in the case of the Port Hedland tides.

## TIDAL COMPUTATIONS AND PREDICTIONS.

A brief explanation of the method of analysing the figures obtained from the records and of making out predicted tide tables for any place will constitute a fitting conclusion to this paper.

First of all from the remarks that have already been made when explaining the "Establishment of a Port," it can be perhaps realised that it would be impossible to calculate a tide table for any port unless observations had been taken there beforehand. This is a point that is overlooked by many people and only goes to prove how inadequate all the theories of the tides really are. From the tide curve, which for preference should consist of a complete year starting from January 1, though this is not absolutely necessary, hourly readings of the heights are extracted and summed in various ways. The figures resulting from this summation are then analysed with the object of determining the actual semi-range of each tide and its phase at some definite epoch.

A brief digression must be made here to explain this last statement. Owing to the earth's revolution round the sun, the earth's rotation on its axis and the moon's revolution round the earth, the two tide-generating bodies, the sun and moon, are continually occupying different positions, not only with regard to the earth but also relatively to one another. And further, owing to the eccentricities of the orbits of the earth and moon, the moon moves at varying speeds round the earth, while the former travels at changing rates round the sun, or in other words the sun *appears* to do so. Realising what this means, some idea of the difficulties to be overcome in a solution of a tide table for any port may be better imagined than described.

If the earth's path round the sun were circular and the moon's motion quite regular, then the prediction of tide tables would be a comparatively easy problem.

And yet it was by applying this principle that Sir George Darwin overcame the difficulty met with in Nature. He split up the sun and moon, as it were, into a number of small bodies and imagined each one to be travelling at a certain fixed rate round the earth. The problem then simply resolved itself into finding the tide produced by each of these imaginary bodies. And, therefore, keeping this point in mind, the actual curve traced from day to day by the tide-gauge pencil may be considered to result from the combination of a number of separate curves drawn by pencils travelling along at different velocities and each one moving through different heights or amplitudes. The question is thus reduced to one of simple harmonic motion and a glance at Plate VIII., Fig. 2, will explain this. Let the point P move regularly round the circumference of a circle and let perpendiculars be continually dropped upon a fixed diameter DD. Then as P moves round the circle, M will move up and down with a speed varying from zero at either end of the diameter to a maximum at the centre. This movement of M is called "Simple Harmonic

Motion" and, if the length of the diameter and the position of P, measured by the angle MOP, are known, then the distance of M from O can be computed.

Now, applying this reasoning to the solution of any one of these simple tides:—The speed is known and therefore the rate at which P travels round the circle. For example, the main solar tide is caused by a sun moving uniformly round the equator at the rate of  $15^\circ$  per hour, namely  $360^\circ$  or once round in one day; the main lunar by a moon moving in the equator at the rate of  $14.4^\circ$  per hour, namely  $360^\circ$  in 25 hours; while the rates of the other fictitious tides are given in the tables of constants. For each tide the semi-range is determined and therefore the diameter of the circle is known. The phase or angle MOP is worked out for a certain epoch—say January 1st, 0hrs. Then from the known speed the alteration of the angle MOP, after any interval, can be estimated and, knowing this angle, the height OM for any instant can be found for each tide. The algebraical sum of all the tides gives the resulting height of water.

This same principle is elaborated in the construction of tide-predicting machines, except that the procedure is reversed.

Analyses of the figures for 1908-12, Fremantle, and 1913, Port Hedland, were completed at the Observatory and appear in the following table:—

THE TIDAL CONSTANTS FOR FREMANTLE AND PORT HEDLAND.

Short Title.	Speed per hour.	Name.	Rough Period.	H. or Semi-Range.				K. or Phase.			
				Fremantle.		Port Hedland.		Fremantle.		Port Hedland.	
				1874.	1908-10.	1911-12.	1913.	1874.	1908-10.	1911-12.	1913.
				Thomson	Cooke.	Curlewis.	Curlewis.	Thomson	Cooke.	Curlewis.	Curlewis.
				feet.	feet.	feet.	feet.	degrees.	degrees.	degrees.	degrees.
K <sub>1</sub>	15.041	Luni-Solar declinational	Diurnal	0.611	0.445	0.389	0.791	..	319	285	295
O	13.943	Lunar ..	do.	0.430	0.322	0.314	0.499	..	324	303	284
P	14.959	Solar ..	do.	0.156	0.144	0.090	0.195	..	313	196	289
M <sub>2</sub>	28.984	Mean Lunar ..	Semi-diurnal	0.154	0.116	0.113	5.509	..	325	303	319
S <sub>2</sub>	30.000	Mean Solar ..	do.	0.145	0.109	0.110	3.352	..	318	318	19
Q	13.399	Greater Lunar Elliptic	Diurnal	0.114	0.083	0.066	0.102	..	333	301	271
		Decl.									
S <sub>1</sub>	15.000	Mean Solar ..	do.	0.039	0.059	0.046	0.115	..	268	259	257
K <sub>2</sub>	30.082	Luni-Solar declinational	Semi-diurnal..	0.051	0.033	0.032	0.800	..	318	338	0
N	28.440	Greater Lunar Elliptic	do.	0.040	0.030	0.034	0.868	..	20	7	292
J	15.585	.. ..	Diurnal	..	0.030	0.022	0.036	..	316	61	302
S <sub>4</sub>	60.000	Mean Solar ..	..	..	0.002	0.008	0.041	..	225	114	189
S <sub>6</sub>	90.000	Do.	..	..	0.001	0.001	0.024	..	167	83	193
T	29.959	Larger Solar Elliptic ..	..	..	0.028	0.008	0.214	..	89	86	99
R	30.041	Smaller Solar Elliptic	..	..	0.024	0.005	0.096	..	237	255	154
M <sub>1</sub>	14.492	Mean Lunar ..	..	..	0.025	0.018	0.030	..	293	304	251
M <sub>3</sub>	43.476	Do.	..	..	0.006	0.002	0.007	..	236	264	233

M <sub>4</sub>	57.968	Do.	..	..	0.009	0.008	0.121	..	312	302	91
M <sub>6</sub>	86.952	Do.	..	..	0.002	0.001	0.065	..	282	327	216
L	29.528	Small Lunar Elliptic ..	..	..	0.010	0.009	0.462	..	328	323	340
V	28.513	Larger Lunar Evec- tional	..	..	0.009	0.007	0.212	..	85	113	294
U	27.968	Compound	..	..	0.010	0.013	0.224	..	24	356	337
2SM	31.016	Do.	..	..	0.007	0.005	0.101	..	200	206	336
MS	58.984	Do.	..	..	0.008	0.010	0.073	..	356	321	278
Sa	0.041	Solar ..	..	..	0.326	0.402	0.372	..	249	226	172
Ssa	0.082	Solar ..	..	..	0.132	0.075	0.148	..	151	225	75
Msf	1.016	Luni-Solar	..	..	0.093	0.052	0.048	..	54	33	187
Mf	1.098	Lunar ..	..	..	0.050	0.024	0.022	..	184	212	307
Mm	0.544	Do.	..	..	0.107	0.085	0.091	..	218	200	86
A <sub>0</sub>	..	Mean Sea Level	..	..	2.055	2.186	16.151	..	..	..	..

An examination of the above figures shows that the Fremantle tides are mainly controlled by the two diurnal tides, K and O, and that the ordinary semi-diurnal lunar and solar ones are comparatively unimportant. This, of course, accounts for the tides being generally diurnal. It should be pointed out that the two tides, K and O, are not exactly diurnal but nearly so, their periods being 23 hours 56 minutes and 25 hours 49 minutes respectively. This gives one of the reasons for the irregularity of the Fremantle tides.

With regard to Port Hedland, it will be seen that the mean lunar and the mean solar quite overshadow all the other tides, and hence the semi-diurnal character of these tides is not surprising.

The diurnals K and O are next in importance but are so small that they only have a chance of making their presence felt about the time of first and last quarter of the moon and are only partially successful.

It has only been possible to analyse the records for this one year, for the simple reason that the services of the tide-computer have been dispensed with, and consequently the work of collecting the hourly readings and performing the preliminary computations has come to a standstill. This is a very great pity and should be remedied as soon as possible. The subsequent year's records are urgently awaiting compilation and in addition observations should be extended to other ports, in the tropics at all events, in order that tide tables from them should be available to shipping.